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MACHO Project Photometry of RR Lyrae Stars in the Sgr Dwarf Galaxy

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ABSTRACT

We report the discovery of 30 type a,b RR Lyrae (RRab) which are likely members of the Sagittarius (Sgr) dwarf galaxy. Accurate positions, periods, amplitudes and magnitudes are presented. Their distances are determined with respect to RRab in the Galactic bulge found also in the MACHO 1993 data. For $R_\odot = 8$ kpc, the mean distance to these stars is $D = 22 \pm 1$ kpc, smaller

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than previous determinations for this galaxy. This indicates that Sgr has an elongated main body extending for more than 10 kpc, which is inclined along the line of sight, with its northern part (in Galactic coordinates) closer to us. The size and shape of Sgr give clues about the past history of this galaxy. If the shape of Sgr follows the direction of its orbit, the observed spatial orientation suggests that Sgr is moving away from the Galactic plane. Also, Sgr stars may be the sources of some of the microlensing events seen towards the bulge.

Subject headings: Galaxies: individual (Sgr) – Galaxies: kinematics and dynamics – Galaxy: bulge – Local Group – Stars: RR Lyrae

1. Introduction

The dwarf galaxy Sgr was discovered by Ibata et al. (1994) in the direction of the Galactic bulge. This is the closest dSph, located at about 25 kpc, and moving away from us at 160 km s^{-1}. The bulk of the stars in this galaxy is very old, 10^{10} yr, with a range in metallicities, $[Fe/H] = -0.5$ to -1.3 (Mateo et al. 1995, Sarajedini & Layden 1995, Fahlman et al. 1996). Sgr is close to pericenter, and it is being torn apart by Galactic tidal forces, judging from its elongated appearance in the sky (Piatek & Pryor 1995, Velazquez & White 1995). Different numerical simulations aimed at tracing the past history of Sgr give density maps and velocity fields which agree with the available observations (Velazquez & White 1995, Johnston et al. 1995). It has not yet been possible, however, to distinguish among a wide range of orbital parameters and models, nor to determine the direction of motion of Sgr (i.e., are we observing it pre- or post-pericenter, and before or after crossing the Galactic plane?).

The MACHO project has identified more than 38000 variable stars in the bulge fields from the 1993 data (Cook et al. 1995). Certain variable stars of different types (SX Phe, Cepheids, W UMa, RR Lyrae, Miras), are good distance indicators, and can be used as probes to study the density of Sgr and of the different Galactic components along the line of sight towards the bulge. The RR Lyrae stars are by far the best distance indicators for an older population object like the Sgr dwarf galaxy (e.g. Nemec et al. 1994), and are the focus of the present study. Our goals are three-fold: 1. identify RRab in Sgr; 2. determine their distance; and 3. measure the shape, orientation, and total extension of this galaxy.

RR Lyrae stars belonging to Sgr were first discovered by Mateo et al. (1995) in a field centered in the galaxy, adjacent to the globular cluster M 54, which is also associated with Sgr (Da Costa & Armandroff 1995). They determined the distance to Sgr,

$(m-M)_0 = 17.02 \pm 0.19$ based on 9 RR Lyrae. More recently, Alard (1996) found more than 300 RR Lyrae stars in a field located in the northern extension of Sgr (in Galactic coordinates), and Mateo et al. (1996) found 3 RR Lyrae stars in a field next to the globular cluster M 5, in the southern extension of Sgr (in Galactic coordinates). The 1993 MACHO fields, located to the north of these previous studies (in Galactic coordinates), add new data, confirming the large extension of Sgr.

2. The RRab Sample

The system and data collection of the MACHO experiment are described by Alcock et al. (1996). Here we consider only the first year data acquired from 1993 February 27 to September 3. There are about 2300 images of 24 bulge fields, containing 12.6 million stars total. The photometric measurements are made with SoDoPhot, derived from DoPhot (Schechter et al. 1994). Light curves for stars identified as variable are phased in order to find periods (Cook et al. 1995). A typical two-color light curve has about 100 points.

The selection of the RRab sample is relatively simple. The variables in the MACHO 1993 data for which a period can be identified are plotted in an amplitude–period plane. RRab have periods within the range 0.3–0.8 days, and amplitudes within the range 0.1–1.2 mag. However, for periods smaller than 0.4 days there are larger numbers of RRc variables, with smaller amplitudes and typical light curve shapes that make them difficult to discriminate from contact binaries. Therefore our selection included periodic variables with amplitudes > 0.2 mag in the MACHO blue band (V_{Macho}), and periods within 0.4-0.7 d. The tighter cut in the amplitudes is imposed to secure good data. About 1700 stars are selected within those cuts. The V_{Macho} and R_{Macho} light curves of all these candidates were inspected in both passbands to decide which ones are bonafide RR Lyrae stars (1173 stars in total). Of these, 44 are duplicates because they are found in the overlap region of MACHO fields. The other 600 stars are mostly contact binaries. Some period aliases are also rejected (see Alcock et al. 1996). In summary, we have imposed stringent selection criteria which ensure the good quality of the sample. The price paid is that the sample is not complete.

Most of the RRab in the final sample belong to the Galactic bulge. Their magnitudes peak at $V \sim 16$, which places them at about 8 kpc. A few, however, are more than twice as far away (30 stars total). Not all of them can be halo RRab, according to current halo models (e.g. Saha 1985). These distant RRab belong to the Sgr galaxy.

Table 1 lists the MACHO catalog of RRab's in Sgr, containing 30 entries. We give

the MACHO identification (field and location), the positions in equatorial and Galactic coordinates, the V_{Macho} periods, the V_{Macho} amplitudes, the σ_V, the chi-square of the phasing fit, the mean V and R magnitudes, and the reddening-independent W magnitudes (defined in Section 4).

3. The Photometry

The photometric calibration of the large MACHO database is challenging. Only differential photometry is needed for a microlensing search, so individual field zero-points and a transformation to the standard system are not priority tasks for the survey telescope. The non-standard MACHO filters have been calibrated with standard Cousins photometry using Landolt standards transferred to LMC fields. We have used these calibrations in the present work. The V_{Macho} and R_{Macho} magnitudes are transformed to standard Cousins V and R magnitudes using the following equations:

$$V = 23.67 + 1.0026\ V_M - 0.156\ (V_M - R_M)$$

$$R = 23.48 + 1.0044\ R_M + 0.182\ (V_M - R_M),$$

where the zero-point is adjusted to match the photometry of stars in common with Cook (1987) and Walker & Mack (1986) Baade's window (BW).

The 24 fields monitored have zero-points that may differ at the 0.15 mag level at most. Cross checks were made with the RRab found in the overlapping regions, and with the OGLE data (V and I photometry) in BW. However, in order to avoid systematic effects, our analysis will be restricted to a differential approach, (i.e. determining relative distances between the bulge and Sgr).

In the regions where two or more fields overlap, we identified a total of 44 bulge RRab with $0.4 < P < 0.7$, where P is the pulsation period in days. Each photometric measurement is flagged for errors due to crowding, radiation blemishes, array defects, bad seeing, and edge effects. A few of the variables were not found in both overlapping fields (some rejected a priori for being period aliases, others was not considered as variables, having fewer unflagged points). Using our internal redundancy, we estimate an upper limit of 93% for the completeness of our RRab sample within the period/amplitude cuts selected.

Using the 44 bulge RR Lyrae stars in overlap regions, we have evaluated the internal uncertainty in the photometry (σ_{V_M}, σ_{R_M}), astrometry (σ_α, σ_δ), period (σ_P), and amplitude (σ_{AV_M}, σ_{AR_M}) determinations. We obtain the following errors: $\sigma V_M = 0.120$, $\sigma R_M = 0.114$, $\sigma_\alpha = 0.58''$, $\sigma_\delta = 0.37''$, $\sigma_P = 0.000054^d$, $\sigma_{AV_M} = 0.12$, and $\sigma_{AR_M} = 0.06$.

The OGLE data in BW (Udalski et al. 1994) provide an independent check on the errors and completeness of our sample. The 9 OGLE CCD's cover the same total area as MACHO field 119. In the overlapping field with OGLE we find 44 RRab within the same period range. Of these, 25 are in common, and the comparison yields: $\Delta\alpha = 0.16\text{''} \pm 0.54''$, $\Delta\delta = 0.24\text{''} \pm 0.42''$, and $\Delta P = 0^d \pm 0.00005^d$, where $\Delta = Macho - Ogle$. These values are consistent with the internal estimates obtained from the overlapping regions of the MACHO fields.

The field of Alard (1996) also overlaps with some of our fields. In this overlap region we find 11 RRab belonging to the Sgr dwarf, and 6 in common with Alard (1996). The differences between the samples are not surprising given the different selection criteria adopted. We emphasize that many of the stars that do not pass our initial periodic variable cuts will be recovered when the 2nd and 3rd year data are analyzed.

4. Reddening

Figure 1 shows the color-magnitude diagram for all the RRab in the MACHO 1993 bulge sample, including RRab belonging to the Sgr dwarf galaxy. The appearance of this color-magnitude diagram is largely dominated by reddening. The direction of the reddening vector is indicated. The reddening is patchy in the MACHO fields towards the bulge, ranging from $E(B-V) = 0.2$ in the outer fields, to $E(B-V) \geq 2$ in the most obscured regions. We will then use reddening-independent magnitudes that assume a standard extinction law for our comparison. These magnitudes, defined as $W_V = V - 3.97 \times (V - R)$, are listed in the last column of Table 1. Note that in the most heavily reddened fields some of the faintest variables will be lost. Because we only reliably detect RRab which are brighter than $V \sim 19.5$, the distance to which we can detect RRab with $0.4 < P < 0.7$ and $A_V > 0.2$ mag depends on the reddening. For $E(B-V) = 0.5$ (typical of the BW field), we would detect RRab located well beyond the known distance of Sgr.

In order to avoid the most heavily reddened regions (where A_V/E_{B-V} may be significantly different from 3.1), the relative distances will be measured using only RRab with $V - R < 0.82$, and located in fields with $b < -4°$.

5. The Periods

There is a strong dependence of RR ab period and luminosity with [Fe/H] (e.g. Sandage 1993a, Jones et al. 1992), in the sense that the more metal–poor RR ab tend

to have longer periods. The effect of metallicity in the period–amplitude plane is clearly illustrated by Figs. 10–12 of Jones et al. (1992). There is also a period dependence on T_{eff} – or color – (e.g. Sandage 1993b, Carney et al. 1992), which cannot be investigated with the present data due to the effect of differential reddening.

These P-L-Z relations have to be taken into account when determining relative distances. Therefore, the relative distance between the RRab in the bulge and in Sgr is computed here using only the RRab in the bulge covering the same period range as the Sgr RRab (*i.e.* $0.46^d < P < 0.66^d$).

The bulge RRab have a mean $[Fe/H] = -1.0 \pm 0.16$ (Walker & Terndrup 1991). The periods listed in Table 1 support the conclusion that the Sgr RRab have longer mean periods, and are therefore more metal-poor *in the mean* than the Galactic RRab in these fields (Alard 1996). The period distribution in Sgr resembles that of the LMC, shown by Alcock et al. (1996). Even though Sgr also has a metal-rich component (Sarajedini & Layden 1995), the bulk of the RR Lyrae stars in this galaxy must be produced by the metal-poor population with $[Fe/H] = -1.3$, as argued by Mateo et al. (1995). The probability of the formation of RR Lyrae stars in a metal-poor population is about a factor of 50 larger than in a metal-rich population (Suntzeff et al. 1991).

6. The Structure of Sgr

The distribution on the sky of the RRab listed in Table 1 is shown in Figure 2. Most of the Sgr RRab are located in the MACHO fields which are well off the Galactic minor axis, and in the lower latitude fields, with only a few of them in the fields closer to the Galactic center, including BW. The MACHO fields are located in the northern–most extension of Sgr (in Galactic coordinates), reaching 3° further away from its center than the fields studied by Alard (1996), who found a declining number of RR Lyrae stars in that direction.

The outer contours of Sgr in the discovery paper by Ibata et al. (1994) cover about 10° along its major axis. However, this galaxy is much more extended. In retrospect, perhaps the earliest observational record of Sgr is the excess of blue stars at about $V = 18$ in the luminosity functions of Rodgers & Harding (1989) for a bulge field at $l,\ b = 10°,\ -22.3°$. These stars with $V \approx 18$, and $0.3 < (B-V)_0 < 0.5$ would be horizontal branch stars at the distance of Sgr. Rodgers et al. (1990) obtained radial velocities and calcium abundances for 18 stars within this color range. Two of these stars (# 2730 and # 3844) have heliocentric radial velocities consistent with Sgr membership ($V_{2730} = 162 \pm 38\ km\ s^{-1}$, and $V_{3844} = 152 \pm 8\ km\ s^{-1}$). Stars associated with Sgr have been found in two other fields

next to that of Rodgers & Harding (1989): Mateo et al. (1996) discovered three RRab associated with Sgr in a field at $l,\ b = 8.8°,\ \ -23.3°$, and Fahlman et al. (1996) detected a sequence of Sgr stars in their color-magnitude diagram for a field at $l,\ b = 9°,\ \ -23°$. The presence of Sgr RRab in the MACHO fields implies that the major axis of Sgr is at least 20° in size, while the minor axis extension is at least 7° in size.

Figure 3 shows the distribution of distance moduli for RRab detected in the MACHO 1993 data. The highest peak at $W_V = 14.6$ is due to the bulge RRab. The second peak at $W_V = 16.8$ is real, and due to the Sgr members. Adopting $R_\odot = 8$ kpc (see the most recent determinations and discussion by Carney et al. 1995), the difference between these peaks, $\Delta m - M = 2.2 \pm 0.1$ mag, locates the Sgr dwarf at $D = 22 \pm 1$ kpc.

Previous distance estimates to Sgr are listed in Table 2. These mean distance determinations range from 24.0 to 27.6 kpc. The present distance D = 22 kpc marks the low end of this distribution. In particular, it is significantly different than the distances of three RRab – $D = 26.4, 27.4$, and 28.2 kpc – in the opposite side of Sgr, measured by Mateo et al. (1996). We argue that the distance spread is real, and due to the fact that Sgr is inclined along the line of sight.

This distance measurement is relative to the Galactic bulge, and largely independent of the RRab absolute magnitude calibration. We have checked for a dependence of this distance with metallicity, by dividing the sample into metal–poor and metal–rich RRab using the period–amplitude diagram. Even though the Sgr sample is small, both longer period (metal–poor) and shorter period (metal–rich) RRab yield similar results. Other effects such as a barred bulge or differential reddening would make the distance shorter.

The various measured distances of Sgr projected in the Galactic x-z plane are plotted in Figure 4. The maximum difference in distances along the line of sight is found between the determination of Mateo et al. (1996) and us. These are two of the most separated fields of Sgr studied so far, about 20° apart. The difference in distance moduli between these two independent determinations is $\Delta(m - M) = 0.47\ mags$, larger than the estimated errors listed in Table 2. The distance of Mateo et al. (1996) is the mean of only three RRab, but it is confirmed by deep color–magnitude diagrams that reach the turn–off of Sgr (Fahlman et al. 1996, Mateo et al. 1996), and therefore cannot be in gross error. Fahlman et al. (1996) list a range of distances, from 26.3 to 28.9 kpc, depending on the parameters adopted for their main sequence fit.

Sgr appears very elongated in the plane of the sky, with an axial ratio 3/1 (Ibata et al. 1995). Two configurations can give rise to such a projected shape: a flat disk seen edge-on, or an intrinsic cigar–shape. However, an edge-on disk is ruled out by our observations, since

this geometry would yield similar distances at both extremes of the galaxy. Thus, Sgr has a cigar shape. Assuming axial symmetry, the line of sight depth of Sgr should be ~ 4 kpc. This is consistent with the observed $FWHM = 0.35 \pm 0.05$ of the magnitude distribution of RR Lyrae stars variables (this work, Alard 1996), again ruling out an edge-on disk with line of sight depth ~ 10 kpc.

This elongated configuration is the predicted effect of a close encounter with the Milky Way, "as tidal effects string stars out along the orbit" (Velazquez & White 1995), and as "the sole effect of tides, as seen from our galaxy, is an elongation of the dSph in the orbital plane" (Piatek & Pryor 1995). Numerical simulations of Sgr's past history show that when the galaxy being disrupted is near pericenter, its major axis is approximately perpendicular to the direction of the Galactic center, i.e. parallel to its orbital motion. Taking into account the radial velocity $V = +160$ km s^{-1}, assuming that the direction of the elongation traces Sgr's orbit, and projecting this as a straight line (first-order approximation), we find that pericenter occurred at a Galactocentric distance of $R \approx 13$ kpc, on the opposite side of the Galactic plane, at $l,\ b \approx (0°, 12°)$. Then, Sgr is presently moving away from the disk, having crossed the Galactic plane at a Galactocentric distance of about 14 kpc (equivalent to 3.5 Galactic scalelengths h_r).

With the measured radial velocity and projection angles of its tangential motion, the orbit of Sgr is determined. However, further confirmation of the orbital direction will come with the measurement of accurate proper motions. We can say that the present analysis agrees with the orbit computed by Velazquez & White (1995), having transverse velocity of 255 km s^{-1}directed away from the Galactic plane, with pericenter and apocenter of 10 and 52 kpc, respectively, and orbital period of 0.76 Gyr. Better agreement is found with the orbit #1 of Johnston et al. (1995), with 1.08 Gyr period, and pericenter and apocenter of 13.4 and 81.5, respectively. In this configuration, the globular clusters associated with Sgr (Da Costa & Armandroff 1995) would be leading the orbit.

However, preliminary results from a proper motion survey show that Sgr is moving towards the Galactic plane (Irwin & Wyse 1996, private communication). Assuming that the distances listed in Table 2 are correct, this would indicate that our main assumption that Sgr is elongated *along* its orbit may not be valid.

7. Conclusions

We have identified 30 RRab members of Sgr, located at the northern edge of this galaxy (in Galactic coordinates). Their positions, magnitudes, amplitudes and periods are

listed in Table 1. The mean estimated distance to these stars is 22 kpc. This is significantly closer than previous distances measured in the center and southern side of Sgr (in Galactic coordinates), as summarized in Table 2. We conclude that Sgr is ~ 10 kpc long, it has a cigar shape, and it is inclined along the line of sight, with its northern side (in Galactic coordinates) being closer (see Figure 4). This information allows us to trace the orbit of Sgr and determine its previous history. Sgr is moving away from the Galactic plane, having passed pericenter which is located in the opposite side of the plane. Its predicted orbit agrees with previous numerical simulations, although the precise orbit needs to be confirmed with accurate proper motions.

The present work is also another step towards the determination of the line of sight distribution of sources for observed microlensing events. In the case of the Sgr dwarf galaxy, its location at 22 kpc makes a very favourable configuration for microlensing by bulge objects at 8 kpc, and since the observed number of microlensing events is about 100, some of these source stars should be in Sgr. However, stars in Sgr cannot explain the high optical depth determined from clump giant sources.

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Table 1. Position, magnitudes, periods and amplitudes for Sgr RRab

Field	Location	RA_{2000}	DEC_{2000}	l	b	P_{V_M}	A_{V_M}	σV_M	χ	V	R	W_V
119	770	18 01 37.26	-30 01 10.6	0.83	-3.55	0.5983	1.038	0.021	37	18.64	18.01	16.15
162	991	18 16 26.30	-26 23 10.2	5.60	-4.67	0.5352	0.573	0.016	19	17.76	17.37	16.20
159	352	18 15 37.10	-25 45 45.6	6.06	-4.21	0.4961	0.819	0.012	52	18.69	18.07	16.23
159	407	18 15 39.42	-25 37 23.2	6.19	-4.15	0.5771	0.727	0.042	12	18.70	18.10	16.32
101	713	18 05 35.60	-27 06 35.4	3.80	-2.89	0.5614	0.781	0.029	7	19.11	18.43	16.41
125	489	18 11 35.69	-31 15 39.1	0.78	-6.03	0.4698	1.213	0.019	154	18.48	17.99	16.52
118	847	17 59 10.31	-29 39 15.1	0.89	-2.91	0.4986	0.839	0.133	14	19.30	18.60	16.53
114	1804	18 03 58.90	-29 13 17.8	1.78	-3.61	0.4824	0.910	0.027	11	19.10	18.54	16.53
104	1156	18 04 13.39	-28 06 50.4	2.77	-3.11	0.5701	0.746	0.028	10	19.24	18.57	16.57
109	557	18 03 19.17	-28 10 32.4	2.62	-2.97	0.5618	0.558	0.008	8	19.24	18.57	16.59
162	878	18 17 27.83	-26 38 43.6	5.48	-4.99	0.5183	0.693	0.026	19	18.70	18.19	16.69
161	822	18 14 19.90	-26 21 43.1	5.40	-4.24	0.4910	0.891	0.025	8	19.67	18.93	16.71
128	1754	18 08 08.28	-29 11 53.5	2.24	-4.39	0.5750	0.944	0.065	16	19.17	18.56	16.74
103	94	18 13 57.11	-27 14 06.3	4.58	-4.58	0.4698	1.245	0.025	48	18.87	18.33	16.76
125	567	18 13 32.26	-31 10 37.4	1.05	-6.36	0.6343	0.741	0.012	43	18.52	18.09	16.81
105	232	18 07 39.45	-27 53 13.1	3.34	-3.66	0.5887	0.632	0.033	5	19.66	18.95	16.83
167	992	18 14 10.55	-27 08 20.1	4.69	-4.58	0.5630	0.886	0.039	21	19.16	18.57	16.83
124	687	18 07 17.53	-31 24 56.6	0.20	-5.29	0.5733	0.850	0.013	16	19.05	18.49	16.84
162	942	18 17 20.76	-26 25 26.3	5.66	-4.86	0.6046	0.624	0.026	6	19.48	18.82	16.87
115	1265	18 09 40.37	-29 40 40.7	1.98	-4.91	0.5736	0.901	0.033	16	18.90	18.39	16.87
128	2147	18 08 12.33	-28 58 03.8	2.45	-4.29	0.6434	0.892	0.047	8	19.63	18.95	16.93
125	149	18 10 17.27	-30 38 16.2	1.19	-5.49	0.5712	0.753	0.016	17	19.26	18.69	16.99
116	318	18 11 56.42	-29 34 29.0	2.31	-5.30	0.6256	0.513	0.006	12	18.87	18.41	17.05
114	1463	18 04 58.98	-29 28 56.3	1.66	-3.93	0.6072	0.422	0.023	4	19.38	18.79	17.06
116	547	18 12 04.01	-29 39 51.5	2.24	-5.36	0.6478	0.796	0.038	13	18.95	18.48	17.10
167	1101	18 13 54.75	-26 49 29.4	4.94	-4.38	0.5663	0.383	0.014	12	18.43	18.10	17.12
162	858	18 17 47.03	-26 38 57.9	5.51	-5.06	0.5418	0.708	0.067	10	19.12	18.62	17.14
111	203	18 12 09.70	-28 40 11.3	3.13	-4.91	0.6459	0.595	0.054	2	19.82	19.20	17.34
125	706	18 13 20.51	-31 03 52.9	1.13	-6.27	0.4891	1.121	0.035	122	18.80	18.44	17.38
162	730	18 15 23.28	-26 34 53.0	5.31	-4.55	0.5247	1.061	0.064	24	19.54	19.00	17.41

Table 2. Distance Estimates for Sgr

l	b	$m-M$	D (kpc)	Method	Reference
4.0	-4.0	16.71	22.0 ± 1.0	RRab	MACHO ($R_{bulge} = 8$ kpc)
4.0	-8.0	16.90	24.0 ± 2.0	RRab	Alard 1996
5.6	-14.1	16.99	25.0	CMD	Ibata et al. 1995
5.6	-14.1	17.00	25.1 ± 4.0	4 globulars	DaCosta & Armandroff 1995
5.6	-14.1	17.02	25.4 ± 1.0	RHB-RGBC	Sarajedini & Layden 1995
6.6	-16.3	17.02	25.4 ± 2.4	RRab	Mateo et al. 1995
8.8	-23.3	17.18	27.3 ± 1.0	RRab, CMD	Mateo et al. 1996
9.0	-23.0	17.20	27.6 ± 1.3	CMD	Fahlman et al. 1996

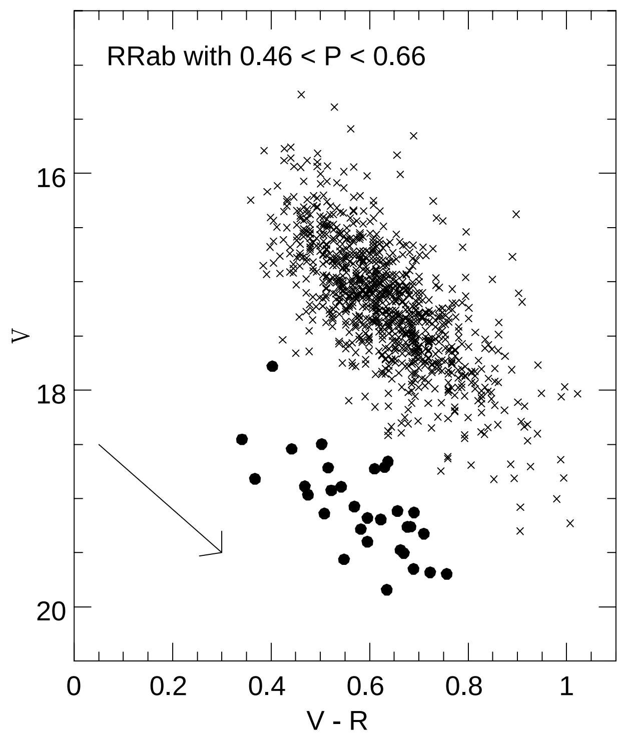

Fig. 1.— Color-magnitude diagram for the RRab in the MACHO 1993 bulge sample. Note the group of fainter RRab belonging to the Sgr dwarf galaxy (filled circles). The direction of the reddening vector is indicated.

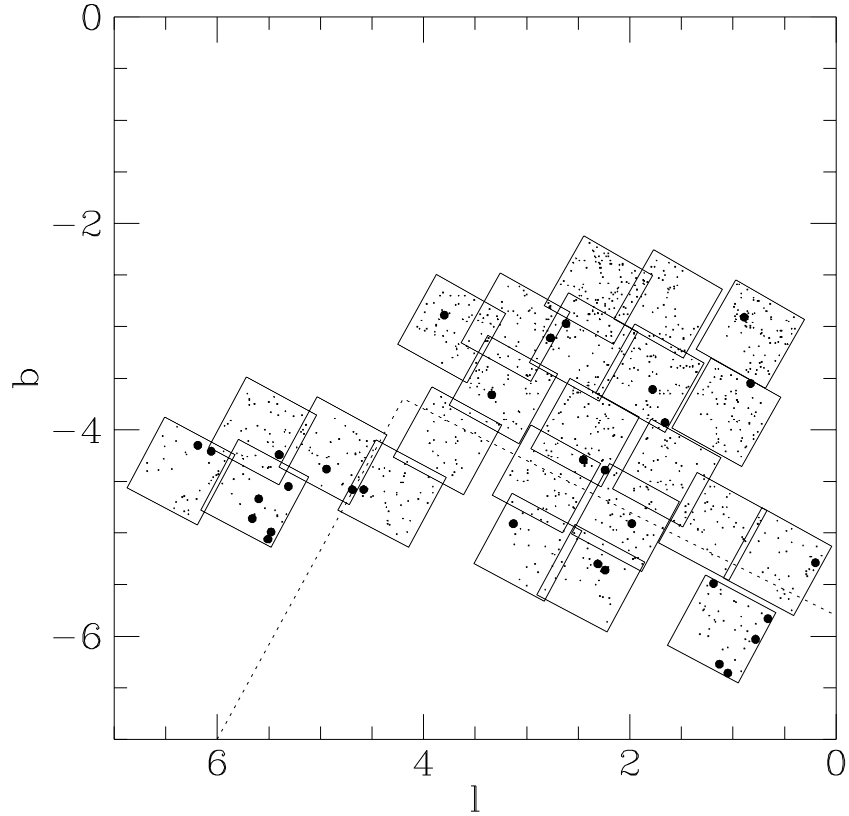

Fig. 2.— The 24 fields surveyed by MACHO in the first year of bulge observations. The location of the bulge and Sgr RRab are indicated with dots and filled circles, respectively. The position of the field observed by Alard (1996) is marked with the dotted line.

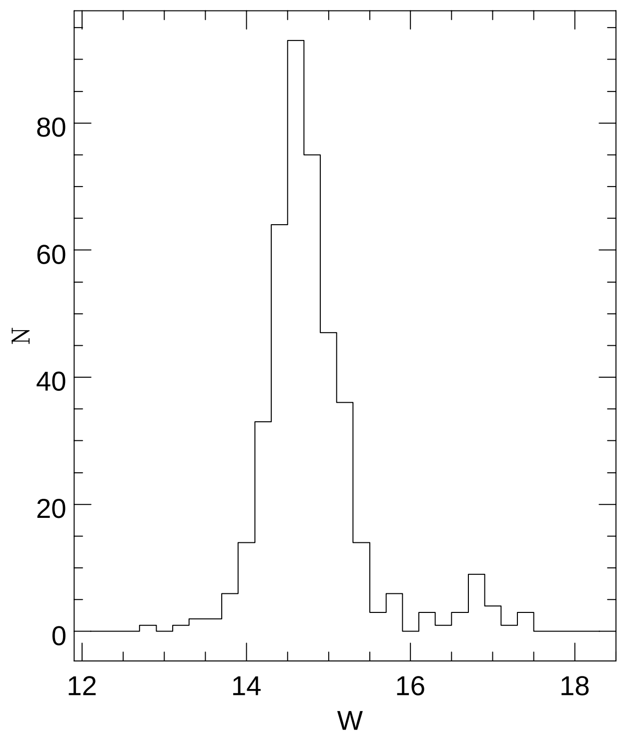

Fig. 3.— Magnitude distribution of the RRab with $0.46 < P < 0.66$, $b < -4°$, and $V - R < 0.8$ in the MACHO 1993 bulge data. The peaks correspond to the Galactic bulge at $D = 8$ kpc, and Sgr at $D = 22$ kpc.

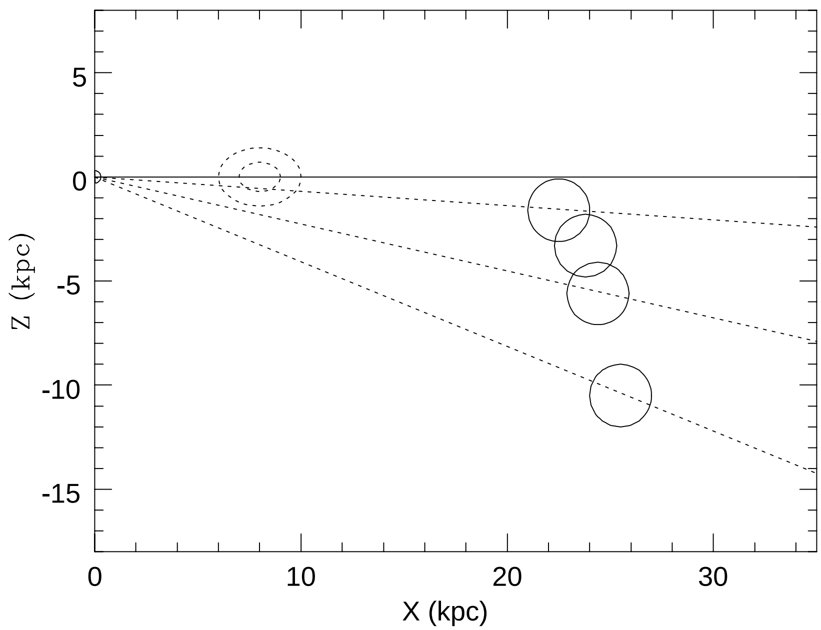

Fig. 4.— Measured distances of Sgr (big circles) projected in the Galactic x-z plane: from top to bottom, the Sgr distance measured here, by Alard (1996), by Mateo et al. (1995), and by Mateo et al. (1996). The Sun is located at (0, 0), and the Galactic bulge at (8, 0).